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Janusz Śledziński

Preliminary Program of Satellite Works Considering the Scientific and Practical Aspects of Applying the Doppler Technique*

1. Introduction

One of the basic, modern, satellite observation techniques which has been widely used recently to fix the positions of geodesic points, the doppler technique is based on utilizing the well-known doppler effect which relies on changes in frequency of the received wave in the case where its source and observer move relative to each other. Doppler surveys were used in the U.S. by Guier and Weiffenbach as early as 1957 to determine orbit elements of the first U.S.S.R. artificial earth satellite, Sputnik I. Shortly afterwards, Frank Trelford McClure suggested that doppler measurements of frequency shift be used to solve the reverse problem, i.e., to determine the position of the observation station when the satellite orbit is known. The main task of designing a system for rapidly fixing the position of points on the earth's surface and constructing and perfecting doppler apparatus was undertaken by the Applied Physics Laboratory of Johns Hopkins University. The Transit system, now known also as the U.S. Navy

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* The work was performed by the educational department satellite group formed by agreement between the Institute of Higher Surveying and Geodesic Astronomy of the Engineering College of Warsaw and the Institute of Land Surveying and Cartography.

Navigation Satellite System (NNSS), commonly used since 1964, was developed. This system was originally designated for the exclusive use of the American Navy for navigational purposes, but in 1967, by a resolution of the vice-president of the United States, H. Humphrey, it was also made available for civilian use. Because of its high accuracy, the system is now widely used for geodesic and geodynamic purposes.

In this work, descriptions of the basic doppler technique and the operating principles of the Transit system will be omitted. Descriptions of the construction and operation of doppler apparatus will also be omitted; the main emphasis will be placed on possible sources of errors in this technique, the need to perform specified scientific research related to the introduction of doppler survey technology and on outlining a general program of work on the use of the doppler technique in land surveying.

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2. Sources of Errors in the Doppler Technique

Among the main errors in doppler satellite survey results are the following:

1. Instrument errors of the doppler receiving equipment on earth and transmitting equipment on the satellite. These errors include:

--errors caused by frequency generator instability (drift) generated on the satellite and the model frequency generator in the receiving equipment on earth,

--errors in emitted time signals, resulting in errors in calculating number of doppler frequency cycles,

--errors resulting from an excessively high level of various radio noises which make it difficult to filter out the actual doppler signal; these errors can be somewhat reduced by using suitable directional antennas.

--various instrument errors which appear to be systematic for particular satellite passes but random for different passes.

2. Errors resulting from the residual effects of ionospheric and tropospheric refraction. Most of the ionospheric refraction is removed automatically by applying two frequencies simultaneously to the survey. The effect of tropospheric refraction errors is eliminated by making appropriate corrections calculated on the basis of an assumed atmosphere model. The residual effect of ionospheric reaction not eliminated from the survey results can be considerable; it is dependent on many factors, such as the sun's activity, time of day, geographic width of observation point, etc. The remaining tropospheric refraction errors evolve from errors in the assumed atmosphere model and actual weather conditions at the time of observation (weather fronts, air density and temperature, etc.). They depend also on accuracy of empirical and theoretical models expressing trospospheric corrections as a function of atmosphere parameters. They also depend on the height of the observed satellite above the horizon.

3. Errors in satellite ephemerides (orbit errors). These errors result because the ephemerides emitted by the satellite every two minutes are prepared a certain time in advance (extrapolated); a change in the actual conditions under which the satellite travel occurs produces a discrepancy in the extrapolated and observed satellite positions. This is affected mainly by a change in density of the upper layers of the atmosphere and the related change in precipitation. This error, just as

the error due to the effect of ionospheric refraction, depends in large measure on the sun's activity. Another important source of ephemeride errors in NNSS satellites is the effect of earth's gravitational field which is not sufficiently known or considered. It should be emphasized that the effect of ephemeride error can be eliminated to a large degree by applying differential observation methods (translocation).

In the future, the accuracy of doppler surveys can be improved by improving the accuracy of satellite orbit determination (defining satellite position) and also improving the accuracy of calculating doppler frequency
15 cycles, thereby increasing model frequency generator stability in the doppler receiver. Attention must also be given to methods for more accurately eliminating refraction effect, mainly tropospheric.

3. Brief Description of Methods for Fixing Doppler Station Positions

Three methods are now known for fixing the positions of geodesic network stations equipped with doppler equipment:

1. Fixing the position of a single network point (single point positioning);

2. Determining coordinate differences of two network points (translocation method);

3. Simultaneous fixing of coordinate points, forming closed network figures (simultaneous point positioning).

The first method of fixing coordinates, individually for particular network points, is one of the satellite dynamic methods and requires a knowledge of exact satellite coordinates at the moment of observation,

which must later be obtained from the NNSS computation center. In this case, the fixed coordinates are burdened with NNSS satellite orbit element fixing errors. This method of coordinate fixing cannot be applied because the precise satellite ephemerides cannot be utilized at the moment of observation.

The translocation method requires simultaneous observation of satellite passes from two doppler stations and makes it possible to more accurately determine *coordinate differences* of these stations. Increased accuracy is possible because orbit element errors (satellite positions), affecting fixing of coordinates of both points in approximately the same way, are largely eliminated in calculating the differences of these coordinates. In the translocation method, only the orbit elements emitted by the satellite are used, and a knowledge of exact ephemerides is not necessary.

The simultaneous method for fixing differences in coordinate points in closed figures requires doppler observations made simultaneously on all points which form a closed figure. This method has many features in common with the translocation method; it is a collection of translocation measurements made simultaneously on all sides of the figure. This method requires a larger number of doppler receivers but permits adjustment of each simultaneous observation by using the geometric relationships of the figure.

4. Advantages of the Doppler Method

In describing briefly the advantages of the doppler technique it should be stated that:

1. The doppler technique brings new elements to the geodesic network

in the form of directly fixed coordinate points or coordinate differences.

2. Because the space coordinate points are fixed by the doppler method in a totally independent way, an accumulation (or propagation) of errors does not take place, as happens in classic type triangulation networks.

/6 3. Doppler surveying and processing of observation data (together with signal filtering) from which coordinate points or coordinate differences are obtained, is completely automatic. Complete data processing programs are available for both single point positioning and translocation.

4. High accuracy in fixing coordinate differences is obtained from a relatively small number of satellite passes. An accuracy of about 1 meter is obtained by observing only several satellite passes, which requires several hours observation duty.

5. Use of the doppler technique in geodesic networks reduces the need for large numbers of triangulation bases and network azimuth surveys; doppler surveys make it possible to fix, with high accuracy, the length and space orientation of long waves, which then permits, with high accuracy, determination of a uniform scale and orientation of the whole network.

6. The doppler technique can be used easily with other satellite techniques. Simultaneous surveys of distance to satellite by the laser method and distance changes by the doppler method (Laser + doppler = range and ranger rate method) are very advantageous.

Due to the advantages briefly described above, the doppler technique is also used to establish new geodesic networks and to modernize and improve existing networks. Work in this area is in an advanced stage in the U.S., Canada, Italy, Australia, South American countries, and some

African countries. The doppler technique is now also the basic technique in studying certain geodynamic phenomena, e.g., terrestial pole displacements.

5. Selection of Doppler Equipment

At present doppler equipment is manufactured by two firms: Magnavox, a government and industrial electronics company in Torrance, California, and a Canadian firm, Canadian Marconi Company, Montreal. Prototype assemblies of doppler equipment produced in various countries, including a French doppler unit designed for the GEOLE commercial system, have not been widely used. Of the two above-mentioned firms which manufacture doppler equipment on a production basis, without question Magnavox has the longest experience as evidenced by continuous improvements in equipment and construction of new, more accurate models. Furthermore, Magnavox works with the institutions controlling the NNSS system, with NASA, the Naval Weapons Laboratory and others, in improving the equipment and maintaining constant compatibility of its parameters with the transmitting equipment installed on the NNSS satellites. Magnavox manufactures several types of doppler equipment designed for military, geodesic and navigation purposes. About 600 various types of Magnavox doppler geodesic instruments are in operation in various countries of the world. In operation also are over 60 military instruments for different
17 types of U.S. military weapons. Brazilian and Australian doppler first-generation Magnavox geodesic instruments, AN/PRR-14 Geoceiver, used for receiving both pairs of frequencies emitted from the NNSS satellites as well as type GEOS instruments, permitted attainment of 1.5-2.5 meters

accuracy with use of precise ephemerides and observations during a one-week period. In 1970, a new commercial version of the Geoceiver was produced, designed for rapid doppler surveys, but with somewhat lower accuracy. Using type MX-702A-3D Land Survey System instruments receiving only NNSS frequencies, the position of a space point could be fixed with 5-10 meters accuracy on the basis of observations made during 1-2 days. Early in 1975, Magnavox modified the MX-702A-3D system, building a third-generation doppler unit known as Geoceiver II (GEO II). Two fundamental elements were improved: the reference oscillator and the real time clock card. In using satellite precise ephemerides, point position accuracy of 1.5 meters based on observations of 30 satellite passes (2-3 days) can be obtained. Using the translocation method, the instrument can provide a fix of x, y, z coordinate differences at about 1 meter accuracy on the basis of just a few satellite passes (several hours of observation). The newest edition of Magnavox doppler instruments appeared recently--the Satellite Surveyor MX-1502. Its basic improvements consist of the addition of magnetic recording of observation results and battery powering of the entire receiver and peripheral equipment.

Taking into account:

--Magnavox's extensive experience in doppler equipment production,

--the firm's continuous contact with the agencies maintaining the world NNS doppler system,

--the high standard of third-generation equipment, as demonstrated by Geoceiver II and Satellite Surveyor,

--the feasibility of obtaining programming for all practical doppler surveys, and

--the wide use of Magnavox instruments in many countries it must be recognized that this firm's instruments are the most reliable and dependable, and that they ensure the highest presently attainable accuracies in doppler surveys.

Difficulties in obtaining precise ephemerides of NNSS satellites make it imperative that translocation methods be used, which means that several doppler receivers are necessary. It should be noted that this method is also very often used by institutions which have access to precise ephemerides because of the higher accuracy of geodesic determinations which can be obtained with it. This is due to the elimination of most of the orbit errors during simultaneous observation of the same satellite position from several points on the earth's surface. Translocation observations made in closed figures are the most advantageous, because they provide for observation adjustment by use of the relationships of the geometric figures.

/8 Taking into account the economic aspects (cost of receivers, economy of labor production in establishing doppler networks) and the technical and scientific benefits resulting from application of the doppler technique, the following complex of doppler equipment is suggested as most advantageous:

1. Three doppler receiver assemblies, Geoceiver II or Satellite Surveyor, with antenna equipment (antenna, antenna amplifier, antenna stand, cable) and punch tape recorder.

2. HP 21 M20 (65K Memory) Minicomputer, equipped with peripheral equipment (teleprinter, interface, tape recorder) together with programming for three-dimensional (3D) determinations by single point positioning and translocation.

3. Essential spare parts for receivers, minicomputer and peripheral equipment.

The decision now before the directors of the Polish geodesic service on the purchase of doppler equipment is extremely urgent. The study of doppler survey technology and the conduct of important scientific and practical work in Poland is dependent upon this decision. Possession of doppler equipment and availability of prepared survey teams is a frequent condition for undertaking foreign jobs in developing countries.

6. Studies on Doppler Survey Technology

Although the doppler survey method has been descirbed in detail in publications and in reports on practical work performed in various countries, and also despite the almost complete automation of the observation process and the obtained data, the obtainment of practical experience and the conduct of specified test studies remains extremely important to ensure the highest possible accuracy of these surveys. Conclusions drawn from our own survey and study materials, confronted with statements in many publications which are sometimes of a distinctly advertising or publicity nature, permit development of some rules for the use of the equipment.

In studying doppler survey technology particular attention should be given in our case, i.e., a case where we do not have the use of satellite precise ephemerides, to studies which would define the most advantageous conditions for applying the translocation method. Studies should also be aimed at obtaining definite experience in the operation of the equipment under conditions which may be encountered on foreign jobs. The scope of

studies related to doppler survey technology should be defined in such a way that they can be completed with intensive work written within one year from obtaining the equipment and putting it into use. This is dictated by the need to practically utilize the equipment on domestic and foreign jobs in the shortest possible time.

The outline of a program of research work related to the development of doppler survey technology is given below. The program presented by the author is based on a study of the extensive scientific literature on
/9 this subject and on the conclusions from discussions conducted in foreign centers which have the doppler apparatus (Wetzell-GFR, Frankfurt-GFR, SAO-U.S.) and also discussions with Magnavox representatives. The scope of necessary studies which must be conducted before production work can be begun is as follows:

1. Study of the accuracy of fixing doppler coordinate points and/or differences of coordinate points in relation to the number of observed satellite passes.

The aim of this study is to determine the required number of satellite passes which must be observed to obtain results of specified accuracy. This element very clearly affects the economics of using the doppler technique to survey geodesic networks. The result of the study should be an empirically defined curve expressing the examined dependence.

2. Study of the accuracy of fixing doppler coordinate points and/or differences of coordinate points in relation to observation of particular NNSS satellites.

Proper functioning of the apparatus located on the satellite is dependent on many factors (transmitter quality, correct power, time clock quality, etc.). Many times the apparatus on the NNSS satellites (e.g. on

the 30120, 30130, 30180 satellites) has not functioned properly. Sometimes small defects in function and failures are corrected, but information sent from the satellites is still of uneven quality. The aim of the study is to group the accumulated observations relating to particular NNSS satellites and make a comparative quality analysis.

3. A study of the accuracy of the translocation method in relation to distance between points and to position of points relative to the direction of satellite travel.

The study relies on conducting translocation measurements between points at various distances relative to each other and located both in the meridian direction (parallel to the direction of satellite motion) and between points distributed in a direction more or less perpendicular to the direction of satellite motion.

It is generally believed that translocation measurement accuracy is not dependent on distances between stations participating in the survey; however, the assertion is frequently made that with an increase in distance, a certain drop in accuracy of fixing differences of coordinates occurs. This appears to be justified in view of observation in the case of larger distances between satellite stations at increasingly large zenith distances, or very unequal zenith distances. The effects of tropospheric refraction can thus greatly lower the fixing accuracy.

The study should be conducted on at least five sections of different lengths, from several hundred meters to about 1,000 km (e.g., 0.5, 15, 60, 200, 800 km). In all studies the same number of passes by the same satellites should be observed; all observations should be made under the most similar conditions possible.

The result of the study should be conclusions defining the possible relationships between point distances, position of points relative to direction of satellite motion and zenith distance of the observed satellite and accuracy of determinations of coordinate differences.

/10 4. Comparison of results of translocation measurements made in one section with those made simultaneously in a triangle and in a geodesic quadrangle.

This study relies on an independent measurement of all six elements (four sides and two diagonals) of the geodesic quadrangle, first separately and then by using three receivers -- simultaneous measurement of triangles formed by the elements of the quadrangle. A comparative analysis of results should show the advantages of conducting three synchronous translocation measurements made under close conditions on the sides of a closed figure affects the accuracy of results would be very significant. Observation material accumulated on such a polygon can also be used for other analyses of accuracy which aim to define the advantageous type and shape of figures.

5. The study should analyze the following factors:

(a) effect of atmospheric conditions (ambient temperature, humidity, pressure),

(b) time of day and year, propagation conditions,

(c) various models for correction considering troposhperic refraction,

(d) effect of point position height above sea level.

These studies require analyses of the selected observation materials made under various meteorological conditions and over a relatively long period of time. An analysis of models for correction considering tropospheric refraction on doppler survey results is one of the most

important effects and therefore a study of this phenomenon should be given a great deal of attention. Results of studies on the effect of the point position height on the accuracy of determining coordinate difference can be very important in undertaking some foreign jobs in high mountainous areas.

6. Studies which compare the linear scale obtained on the basis of doppler measurements with the geodesic network scale determined on the basis of classic measurements.

It is a known fact that the doppler network scale differs by about $0.9-1.1 \cdot 10^{-6}$ from the classic network. This is due in large part to acceptance of another unit reference system (system scale), in which NNSS satellite orbit elements are given, and systematic errors of ephemerides of these satellites due to the effect of errors in the accepted model of the earth's gravitational field. An examination of this problem is very important in using doppler surveys to establish new geodesic networks and it should be studied in particular detail. The study should be based on doppler surveys made on a suitably selected test polygon. Studies should be made on sections from several hundred to several thousand kilometers. Under domestic conditions the study should be made on a polygon designed to make use of the largest possible distance between points. In the future, studies of this problem should be made by taking measurements along the west-European base measured in
/11 connection with the creation of a world satellite geometric system developed by Schmidt. The length of this base, running from Tromso in Norway to Catania in Sicily was measured recently with great precision by ground methods and a comparison of its length with doppler survey results made on the entire base or a portion of it, would give an unusually interesting picture on the value of scale obtained by the

doppler instruments. It should be remembered that in addition to the above-mentioned reasons causing the differences in scales of the doppler and classic networks, certain differences can be caused by instrument errors and inaccurate calibration. It is necessary, therefore, to make periodic examinations of the instruments at a selected test section.

7. Comparison of accuracy in fixing difference of $\Delta \underline{x}$ and $\Delta \underline{y}$ coordinates with accuracy of difference of $\Delta \underline{z}$ coordinates.

When doppler receivers were first used for three-dimensional fixing of point positions (symbol "3D"), the differences between the accuracies in fixing differences of $\Delta \underline{x}$ and $\Delta \underline{y}$ coordinates and $\Delta \underline{z}$ coordinates were quite high. Further study indicated a decrease in this difference and it appears that the present accuracy of fixing all differences of coordinates is the same.

8. Study of the accuracy of fixing by single point positioning using only the extrapolated orbit elements emitted by the satellite.

Results of this study will answer the question, what actual accuracy of single point positioning can be achieved using measurements made by one doppler receiver. It is necessary also to find out how an increase in the number of observed satellite passes affects the accuracy of point positioning and to establish a minimal, economically justified optimum number of passes essential to fix positions with a specified accuracy. An appropriate analysis of results will also give an opinion on the extrapolation accuracy of the orbit elements emitted by the satellites.

In addition to the above-mentioned studies, it is necessary also to determine whether the apparatus is functioning correctly, e.g., stability of the model receivers' frequency generators over a long or short period, the real time clock card, operation of the self-calibrating

unit, cooperation of the perforating unit with the receiver, etc. These instrument examinations should be made before proceeding to the above-mentioned studies.

All these studies require detailed programming and coordination, for within the relatively short period of one year a large amount of material must be collected, enough from which to draw practical conclusions. The observation program should be planned so that the same observation material, appropriately arranged, can be used for further analyses. The following geodesic centers can be chosen as doppler stations: Borowa Gora, Jozefoslaw, ATR-Olsztyn, the Polish Academy of Sciences station at Borowiec, the Naval College at Gdansk or in Szczecin, etc. However, surveys should also be made at field stations. In translocations studies it is advisable to set one instrument on the reference point permanently, but change the position of the remaining doppler receivers.

/12 The result of the studies on the technology of doppler surveys should be a report containing:

1. A detailed set of instructions for making doppler surveys at the observation post.

2. Results of studies of all factors affecting doppler fixing accuracy.

3. Conclusions, recommendations and instructions on correct use of doppler apparatus based on the studies.

7. Theoretical Studies on the Use of Satellite Surveys in Basic Astronomic-Geodesic Networks

Simultaneously with the studies aimed at introducing the newest satellite technique, the doppler technique, into geodesic production,

studies must be made on ways to utilize satellite surveys in basic networks. This problem is more universal, it is linked to the use of satellite surveys in astronomic-geodesic networks generally and can be considered only in the aspect of a complex analysis of the relationship and role of satellite surveys in forming satellite-astronomic-geodesic networks. In view of the rapid development of various satellite techniques and the resultant accumulation of a wealth of valuable observation material, the acceleration and intensification of these studies is a matter of unusual importance and urgency. An appreciation of the importance of these problems has been expressed in the formation of new sections and working groups of international scientific organizations (MUGG, KAPG) whose task it is to initiate and coordinate such studies.

Obviously the Polish photographic observation stations (Olsztyn, Poznan, Borowiec centers) should continue to expand their activities. Research on the construction and improvement of the second generation laser (Borowiec) should be further intensified, practical work in introducing the doppler technique should be begun -- to which this article should contribute. A detailed plan should be worked out for using the existing satellite apparatus to do the practical work related to the formation of a satellite-astronomical-geodesic network. Here the author expresses his own opinion that despite great economic difficulties, lack of equipment and certain staffing problems, the period of conducting trials and experiments is still much too long and too few projects are developed for practical utilization of existing apparatus capabilities. There is also a lack of proper organization and coordination of studies and work in this area.

Theoretical studies concerning use of satellite measurements in astronomic-geodesic networks should, as mentioned, involve all types of

surveys (photographic, laser, doppler), covering the specifics of each of these satellite techniques. The statement sometimes made that photographic observations have become obsolete and have been replaced by other more accurate and more economical satellite techniques, is erroneous. The irreplaceable advantage of the photographic method, which other satellite
/13 techniques lack, is that the directions to the satellite determined in all observation points are referenced to a uniform system of star coordinates. New satellite techniques introduced two new basic elements, whose methods of use in basic networks should be the subject of detailed studies. These elements are long line azimuths and long bases. Introduction of these elements demands that certain concepts be revised and that the new role of some classic elements (e.g., Laplace azimuths) in the new satellite-astronomical-geodesic network be defined. Another important problem is a determination of the required number of satellite points, their distribution in the network and use of appropriate satellite techniques. This problem is linked to the relationship of the satellite network to the classic type geodesic network. An unsolved problem is the reduced satellite observation on the geoid and reference ellipsoid, and also selection of the best ellipsoid for the satellite-astronomical-geodesic network in large areas (continental or world networks). An analysis of the accuracy of basic coordinate systems, in which sizes measured by satellite techniques are obtained, is an important task in evaluating the feasibility of properly using satellite surveys in basic networks. Of considerable importance is an analysis of the accuracy of determining the fundamental astronomical system of coordinates, and the mean terrestrial coordinate system, and also the accuracy of parameters which permit mutual transformation between these systems. The matter of coordinate systems has been given a great deal of attention recently in connection

with the increased accuracy of satellite surveys. An indication of this was the International Colloquium MUA No. 26, "On Reference Coordinate Systems for Earth Dynamics", organized in 1972 in Torun by the Smithsonian Astrophysical Laboratory and the Institute of Land-Surveying and Geodesic Astronomy, Warsaw Engineering College.

Following are the most important problems and issues whose resolutions have practical aspects:

1. Analysis of the feasibility of using long bases measured by satellite techniques to determine the scale of modern satellite-astronomic-geodesic networks.

2. Analysis of the feasibility of using long line azimuths measured by satellite techniques to orient basic networks in large areas and determine the mutual relationship between these azimuths and Laplace azimuths occurring in classic networks.

3. Study on determining the true density of satellite points in satellite-astronomical-geodesic networks and their distribution.

4. Study of the problem of satellite network reduction on the reference ellipsoid.

5. Studies concerning selection and orientation of the reference ellipsoid.

6. Evaluation of the accuracy of real applied coordinate systems and parameters of transformation linking these systems.

7. Studies on methods of adjusting satellite-astronomical-geodesic networks.

The use of satellite techniques in geodynamic problems demands a separate program and discussion.

/14 It should be stated that theoretical studies concerning the above problems are already in a highly advanced stage in some Polish scientific centers. Extensive theses and doctoral dissertations are already being prepared on this subject.

8. Conclusions

In recapitulating this work, the author wishes to present several conclusions, only a partial realization of which would contribute to more rapid progress in studies on use of satellite surveys to strengthen the construction of astronomic-geodesic networks and better practical utilization of apparatus owned by Polish satellite centers.

1. Wide discussion should be initiated on the subject of the form, construction and principles of creating a modern satellite-astronomical-geodesic network and the role of satellite surveys in such a network. Closer international cooperation should be developed in this area, and the design of such a network should be prepared. Theoretical studies relating to the use of satellite techniques for work on a modern satellite-astronomical-geodesic network should be expanded.

2. Activities of stations making satellite observations by photographic and laser methods should continue to be expanded. Photographic satellite stations should work towards fuller automation of the observations process and the preparation of results. However, an activity program for these stations (centers) should be defined as rapidly as possible, giving priority to work of a scientifically practical nature.

3. Doppler apparatus should be purchased as quickly as possible and

intensive study should be begun on developing a doppler survey technology. This technology should be developed in a period not exceeding one year and should cover certain aspects of the use of this apparatus on foreign jobs. A detailed program should be prepared on the use of this purchased apparatus.

4. In view of the great advantages created by simultaneous satellite observations made by various satellite techniques, a station equipped with apparatus for photographic, laser and doppler observations should be organized.

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Leading programme of satelite works considering scientific and practical aspects of Doppler technique

Summary

Investigation programme concerning elaboration of technologie of satellite Doppler measurements (§ 6) as well as application of satellite observations to establishment of basic geodetic networks (§ 7) have been discussed in the paper. Specific errors of satellite Doppler observations (§ 2) and their sources have been given. Particular adventages of satellite Doppler observations for establishment or strengthening of geodetic control have been considered. Development of the MAGNAVOX Doppler receivers has been shortly characterized (§ 5). A good deal of attention has been engaged in investigation programme of practical problems concerning application of translocation method to determination of differences of coordinates. General conclusions concerning development of Polish practical and scientific undertakings on application of satellite measurements to modern geodetic networks establishment have been pointed out.

Jan Kryński

Application of Low-Low Satellite Observations to Local Geoid Determination*

1. Introduction

In the Wolff [9] concept, which is based on measurement of the relative velocity of two satellites orbiting in a common semi-circular orbit, the relationship between changes in satellite speed and anomalies of the earth's gravitational field is employed. Changes in absolute velocity of a satellite moving in a circular orbit may be treated as the effect of irregularities of the earth's gravitational field in the global sense, if nongravitational effects are disregarded. In these changes, both long wave and short wave effects are considered.

Using the relative velocity of two satellites whose reciprocal distance does not exceed several hundred kilometers reduces the problem to an examination of the short wave differential effect. Hence, as can easily

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be seen, the Wolff concept can be applied to determining local changes in the earth's gravitational field, and particularly, to the local geoid.

A discussion of the method's accuracy was begun by Balmino [1]. Using integral energy he formulates the relationship between the accuracy of observation of relative velocity and the accuracy of determining the anomaly of mean Δg and the magnitude of the area represented by this anomaly. He concludes that for a specified satellite height the accuracy of relative velocity measurement should be inversely proportional to the reciprocal distance of the satellites.

The subject of this work is the examination of the use of low-low satellite observations in local geoid determination. It is advantageous that from the standpoint of practical use, local applications do not require global observations at the satellite height. Furthermore, very modest observational materials can be used, and the global interaction of combinations of heterogeneous data can also be examined. Observations of low-low satellites can be used not only for areas covered by ground observations, but also for totally uncovered areas. In this case, geoid height calculated from one of the global solutions will be examined

/18 together with the observations of relative velocity of low-low satellites. Thus, local geoids cannot be corrected until an appropriate amount of information for obtaining a better solution is available.

Relative velocity of low-low satellites can be measured either by the laser technique or by using doppler apparatus. To avoid excessively optimistic conclusions, various measurement accuracies were assumed.

The collocation method for solving the problem was particularly useful. It permits an evaluation of the anticipated accuracy on the basis

of a covariant function and accuracy of observation data. By using collocation it is possible to develop, in an unqualified way, such heterogeneous data as: geoid undulation, gravimetric anomalies and low-low satellite relative velocity observations.

The diagram for using collocation was given in the author's work [2]. In selecting the regional covariant function, the reasoning described in publication [3] was applied. Finally a logarithmic type model was chosen, with a k_l factor expressed as follows:

$$k_l = \frac{1}{(l-1)(l-2)(l+B)} \tag{1}$$

while the numerical value of constant B was taken from report [8]. As covariant function parameters A, s, L [3] were assumed at numerical values:

$A = 607.57 \text{ mgal}^2$, $s = 0.998444$, $L = 7, 12, 18, 24$,

where A complies with the definition stated in [8] and represents a constant value for gravimetric anomaly covariant function.

2. Numerical Problems

The problem of formulating an observation expression and determining basic covariance functions is treated in [2]. From the discussion conducted in that work it appears that in practical applications the following observation equation can be conveniently used:

$$\dot{\varrho}^2 - \dot{\varrho}^{N2} = 2\dot{\varrho}^N \Delta\dot{\varrho} + \Delta\dot{\varrho}\Delta\dot{\varrho}. \tag{2}$$

Signal $\underline{S}_t$ limited to the linear portion is expressed by the formula

$$s_t = 2\dot{\vec{\varrho}}^N \dot{\vec{\Delta}}\varrho. \tag{3}$$

The expression describing covariance in this case will take the form:

$$\mathrm{cov}(s_t, T_Q) = 2\dot{\vec{\varrho}}^N[\overline{\overline{K}}(S_{2_t}, Q) - \overline{\overline{K}}(S_{1_t}, Q)], \tag{4}$$

$$\mathrm{cov}(s_t, s_u) = 4 \sum_{i=1}^{3} \sum_{j=1}^{3} \dot{x}^N_{t\,i} \dot{x}^N_{u\,j} \int_{\tau=t_0}^{t} \int_{v=u_0}^{u} L^{\tau v}_{ij}\, dv\, d\tau, \tag{5}$$

where

$$L^{\alpha\beta}_{ij} = \sum_{l=1}^{2} \sum_{k=1}^{2} (-1)^{(k+l)} \frac{\partial^2 K(P_{l_\alpha}, P_{k_\beta})}{\partial x_{P_{l_{\alpha}}{}_i} \partial x_{P_{k_{\beta}}{}_j}}, \tag{6}$$

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$$\overline{K}(S_{i_t}, Q) = \int_{\tau=t_0}^{t} \nabla_{(S_{i_\tau})} K(S_{i_\tau}, Q)\, d\tau, \quad i = 1,2. \tag{7}$$

$$K(P, Q) = \sum_{n=L}^{\infty} k_n \left(\frac{R_B}{r_P r_Q}\right)^{(n+1)} P_n(\cos\psi). \tag{8}$$

Use of the COVAX procedure developed by Tscherning [7] to compute covariance is possible after making some slight modifications in expressions (4) and (5).

$$\nabla_{(S_{i_\tau})} K(S_{i_\tau}, Q) = \nabla_{(S_{i_\tau})} \mathrm{cov}(T_{S_{i_\tau}}, T_Q) =$$
$$= \left[\mathrm{cov}\left(\frac{\partial T_{P_{i_\tau}}}{\partial x_{1P_{i_\tau}}}, T_Q\right), \mathrm{cov}\left(\frac{\partial T_{P_{i_\tau}}}{\partial x_{2P_{i_\tau}}}, T_Q\right), \mathrm{cov}\left(\frac{\partial T_{P_{i_\tau}}}{\partial x_{3P_{i_\tau}}}, T_Q\right)\right]. \tag{9}$$

Let us note that

$$\frac{\partial T}{\partial x_i} = \frac{\partial T}{\partial r}\frac{\partial r}{\partial x_i} = \frac{\partial T}{\partial r}\frac{x_i}{r}. \tag{10}$$

Thus

$$\nabla_{(S_{l_\tau})} K(S_{l_\tau}, Q) = \operatorname{cov}\left(\frac{\partial T_{P_{l_\tau}}}{\partial r_{P_{l_\tau}}}\frac{1}{r_{P_{l_\tau}}}, T_Q\right)(x_{1P_{l_\tau}}, x_{2P_{l_\tau}}, x_{3P_{l_\tau}}). \tag{11}$$

Stating

$$M_i^\tau = \sum_{j=1}^{2}(-1)^j x_{i_{P_{j_\tau}}} \operatorname{cov}\left(\frac{\partial T_{P_{j_\tau}}}{\partial r_{P_{j_\tau}}}\frac{1}{r_{P_{j_\tau}}}, T\right) \tag{12}$$

we obtain

$$\operatorname{cov}(s_t, T_Q) = 2\sum_{i=1}^{3}\dot{x}_i^N \int_{\tau=t_0}^{t} M_i^\tau d\tau. \tag{13}$$

Similarly we can convert expression (5). We then have

$$\frac{\partial^2 K(P_{l_\tau}, P_{k_v})}{\partial x_{iP_{l_\tau}}\partial x_{jP_{k_v}}} = \frac{\partial^2}{\partial x_{iP_{l_\tau}}\partial x_{jP_{k_v}}}\operatorname{cov}(T_{P_{l_\tau}}, T_{P_{k_v}}) = \operatorname{cov}\left(\frac{\partial T_{P_{l_\tau}}}{\partial x_{iP_{l_\tau}}}, \frac{\partial T_{P_{k_v}}}{\partial x_{jP_{k_v}}}\right) \tag{14}$$

Utilizing (10) and applying the law of covariance we obtain

$$\frac{\partial^2 K(P_{l_\tau}, P_{k_v})}{\partial x_{iP_{l_\tau}}\partial x_{jP_{k_v}}} = x_{iP_{l_\tau}} x_{jP_{k_v}} \operatorname{cov}\left(\frac{\partial T_{P_{l_\tau}}}{\partial r_{P_{l_\tau}}}\frac{1}{r_{P_{l_\tau}}}, \frac{\partial T_{P_{k_v}}}{\partial r_{P_{k_v}}}\frac{1}{r_{P_{k_v}}}\right). \tag{15}$$

Stating

$$M_{ij}^{\tau v} = \sum_{l=1}^{2}\sum_{k=1}^{2}(-1)^{(l+k)} x_{iP_{l_\tau}} x_{jP_{k_v}} \operatorname{cov}\left(\frac{\partial T_{P_{l_\tau}}}{\partial r_{P_{l_\tau}}}\frac{1}{r_{P_{l_\tau}}}, \frac{\partial T_{P_{k_v}}}{\partial r_{P_{k_v}}}\frac{1}{r_{P_{k_v}}}\right) \tag{16}$$

we obtain

$$\mathrm{cov}(s_t, s_u) = 4 \sum_{i=1}^{3} \sum_{j=1}^{3} \dot{x}^N_{t_i} \dot{x}^N_{u_j} \int_{\tau=t_0}^{t} \int_{v=u_0}^{u} M_{ij}^{\tau v}\, d\tau\, dv. \qquad (17)$$

In formulas (13) and (17) describing covariance, there appear integrals of certain complex functions of potential, disturbing T calculated along the satellite orbit. In practice, integrated orbit sections are very short, so integration can be replaced with addition.

/20 Let Δt be the assumed fixed integration step. Determining

$$n = E\left(\frac{t-t_0}{\Delta t}\right) \quad \& \quad m = E\left(\frac{u-u_0}{\Delta t}\right), \qquad (18)$$

where n and m express the total number of integration steps correspondingly in intervals (t_0 , t) and (u_0 , u). Covariances (12) and (16) can be written as follows:

$$\mathrm{cov}(s_t, T_Q) = 2 \sum_{i=1}^{3} \dot{x}^N_{t_i} \left\{ \sum_{l=1}^{n} M_i^l \Delta t + M_i^{l+1}(t-t_0-n\Delta t) \right\}, \qquad (19)$$

$$\begin{aligned} \mathrm{cov}(s_t, s_u) = 4 \sum_{i=1}^{3} \sum_{j=1}^{3} \dot{x}^N_{t_i} \dot{x}^N_{u_j} \Big\{ \sum_{l=1}^{n} \Big[\sum_{k=1}^{m} M_{ij}^{lk} \Delta t + M_{ij}^{l(m+1)}(u-u_0-m\Delta t) \Big] \Delta t + \\ + \Big[\sum_{k=1}^{m} M_{ij}^{(n+1)} \Delta t + M_{ij}^{(n+1)(m+1)}(u-u_0-m\Delta t) \Big] (t-t_0-n\Delta t) \Big\}. \end{aligned} \qquad (20)$$

Covariances described by formulas (19) and (20) are relatively easy to calculate using a computer. However, this requires a knowledge of position vector constituents and relative velocity of both satellites. In calculating orbits, the FOCFIN program, developed by the author [4]

according to the two fixed centers theory, was used. A separate algorithm was also developed as well as a STS computer program used to simulate temporary satellite positions and velocities for satellite pair relative velocity observation moments.

3. Geoid Determination Based on Low-Low Satellite Observation

The subject being considered in this section is a discussion on the accuracy of geoid undulation correction calculated from a global solution by adding information derived from observation of low-low satellite relative velocity. Ground observations are not considered here, hence the results given in this section reflect accuracies which can be expected for areas not covered by ground observations.

Analysis results can be grouped as follows:

a. Observation distribution,

b. Optimal satellite height,

c. Effect of measurement errors,

d. Orbit parameters and reciprocal position of satellite pairs.

In local applications observations can usually be limited to those on the outside of a certain circle (critical circle), in the center of which is the determined point. The correctly defined radius of the critical circle is the correlation distance characteristic for a given covariance function of a given set of observations. The determination accuracy of a given quantity depends on the number and distribution of observations at points lying inside the critical circle. The number of covariances, whose calculation in this case is very time-consuming, increases very rapidly along with an increase in the number of observations; therefore, before

beginning a systematic analysis, it is essential that an optimal configuration be found. The problem of defining optimal configuration was formulated as follows: In the coordinate system (r, φ, λ), a point is given on the

/21 earth's surface (h = 0 km), in which the undulation of geoid N is known from one of the global solutions with an accuracy of ± 3 m. In the same system low-low satellite relative velocity observations are given with an accuracy of ± 0.1 mm/sec made in a certain area at a height of 400 km above the considered point. An observation configuration should be found which will optimally contribute to correcting the determination accuracy of N, while taking into account the limited number of observations.

Conclusions describing the search for optimal solutions have been drawn from an analysis of a series of considered examples. Therefore, relative velocity observations should be distributed so that their program on the sphere constituted a symmetric system relative to the sphere of the determined point of coordinates φ, λ. Observations should be uniformly distributed in an area measuring about $7^{\circ} \times 7^{\circ}$, and distances between observations along the orbit should not differ much from the intervals between observation profiles. It should be noted that the correlational distance of the covariance function is dependent on height and so the measurements of the area, inside which observations are considered, and the distance between observations, are functions of height. An optimal configuration composed of five symmetrically arranged observations was used in further calculations.

The search for the optimal height on which satellite observations are made may appear to be unjustified in view of the frequently expressed view that in order to study the gravitational field, satellites orbiting as

close as possible to Earth should be utilized. Figure 1a, however, indicates that the problem of satellite height demands a detailed examination from the standpoint of local applications. Figure 1a gives mean error $\underline{m}_{\underline{N}}$ of geoid undulation determination in relation to satellite height $\underline{h}$. The mean error reaches a minimum at a height of about 300 km, and geoid determination accuracy drops both in the case of smaller as well as larger heights. It

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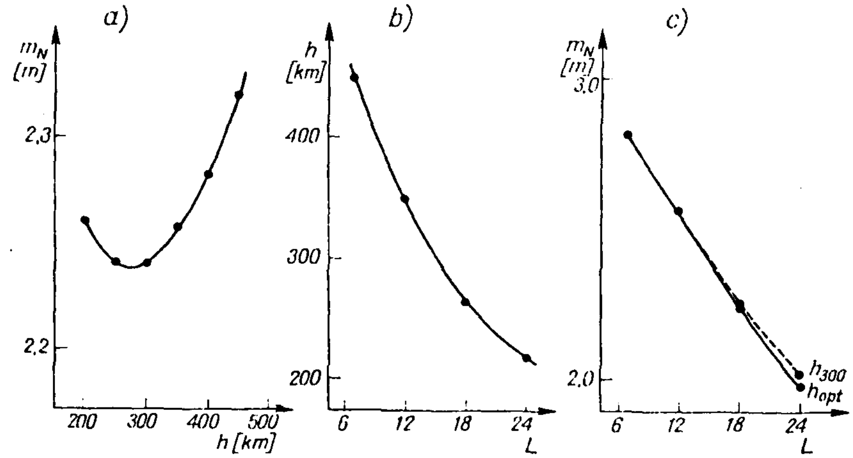


Fig. 1 a. Optimal satellite height for reference field $\underline{L}$ = 18; b. Relationship of optimal height to degree and order of reference field; c. Accuracy of geoid undulation determination from observations at a height of 300 km and at an optimal height, as a function of degree and order of reference field.

/22 appears that the optimal height is dependent on the selection of $\underline{L}$, i.e., on the degree and order of the assumed field of reference. This relationship is shown in Fig. 1b. Along with increase in $\underline{L}$, a decrease in optimal height is noted. Furthermore, the decrease in optimal height is accompanied

by a drop in mean error in estimated quantity. This is indicated in Fig. 1c, where curve $\underline{h}_{opt}$ denotes mean error corresponding to optimal height, and curve $\underline{h}_{300}$ illustrates mean error corresponding to height $\underline{h}$ = 300 km for reference field degree and order $\underline{L}$.

From an applications viewpoint, the physical interpretation of these results is interesting. As is known, the harmonic factors of lower degrees and orders produce the most significant geoid deformation, and thus most heavily contribute to geoid undulation $\underline{N}$ determination. Use of the reference field is linked to geoid variation reduction. In the case of a low degree and order reference field, reduced variations of the geoid can be both global as well as local. These variations can be determined only from measurements made in limited areas. Because global effects have a greater effect on the solution, use of observations which represent global effects well are preferred. This, however, requires toleration of some losses in locally derived information. Such a situation occurs when we consider relative velocity measurements of a satellite pass in high orbit. Such measurements represent global effects much better than local effects, and therefore give better results in using a low degree and order reference field in comparison with the same observations made in low orbit. The situation changes when a reference field of higher degree and order is utilized. Then global effects are represented by the reference field, and in such a case in order to obtain a good solution which takes local effects into account, low-orbit observations should be used.

The selection of a suitable reference field is a problem of practical importance. For a proposed height of $\underline{h}$ = 300 km, as shown in Fig. 1c, a reference field in the range 6 to 24 degrees and order can be used. In this case, then, we have a large freedom of selection of reference field,

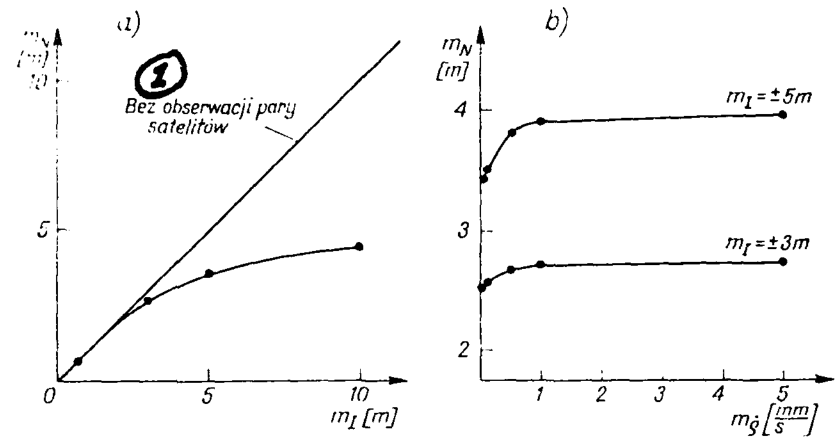
which contrary to appearances is fully justified. The observed signal contains only a portion of the information derived from radial gradients, and so is relatively weak. Hence certain changes appear in the estimated accuracy of geoid undulation determination along with the variable of satellite height, and optimal height can be selected from a relative large height range, reaching several hundred kilometers.

The formula describing the matrix of error covariance shown in reference [2] can be employed only when all factors in the reference field are sufficiently well determined and no significant correlations appear among them. However, none of the now known models of the earth's gravitational field fulfill this type of assumption. In relation with the above, reciprocal correlations must be considered, and so in these cases other formulas must be used in the calculating process (e.g. Rao [5]).

Another approach which avoids complications produced by reciprocal correlation of harmonic factors, is that of limiting oneself to a small portion of the model field, in which correlations are negligible, that is, /23 to lower order harmonics. In this case, however, we encounter a large increase in mean error. The above observation plays a very important role in this discussion. Because of it we were able to avoid many mistakes based on drawing excessively optimistic conclusions.

During calculations we used the limited model reference field accepting $\underline{L} = 12$. Based on Schwarz's [6] studies, we must believe that an assumption of interdependence of factors in such a well-chosen model has no real effect on the results.

Figure 2a shows the effect of changes in initial accuracy of geoid $\underline{m}_I$ undulation, which fluctuates in the 0 m to $\pm$ 10 m range, on the accuracy of $\underline{N}$ determination during observation of a satellite pair. The curve shown on



Key:

1. Without satellite pair observation

Fig. 2. a. Share of satellite pair observation in adjusting geoid undulation determination; b. Effect of mean errors of satellite pair observation on accuracy of geoid undulation determination.

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the figure corresponds to reference field L = 12 and satellite height 350 km. As can be readily seen, use of satellite pair observation examining a geoid gives rational results even when a good model of gravitational field is not available. Accepting initial accuracy of geoid undulation determined on the basis of one of the global solutions as ± 3 m, we can contribute only slightly to its correction using satellite pair observation. The above statement also explains the previously obtained equivocality in determining optimal height and also makes it easier to interpret the effect of observation errors on quantity determination.

Conclusions can be drawn from Fig. 2b on the effect of measurements of satellite pair relative velocity on accuracy of geoid undulation determination N. Calculations were made using the previously mentioned optimal configuration

of observations made at a height $\underline{h}$ = 300 km, whose mean errors ranged from 0.1 mm/s to 5 mm/s. Two cases were considered: in the first, the initial accuracy of geoid $\underline{m}_I$ was taken as $\pm$ 3, in the second, $\underline{m}_I = \pm 5$ m. In the first case we are dealing with a very weak signal and even at very high
/24 satellite pair relative velocity observation accuracy large improvements in correction of results cannot be expected. The relationship between observation errors and accuracy of geoid determination is much clearer in the second case, i.e., when $\underline{m}_I = \pm 5$ m. Differences in accuracy of determination $\underline{N}$ become greater if observation errors are below the $\pm$ 0.5 mm/sec level, but where observations are burdened with errors exceeding $\pm$ 0.5 mm/sec, a very slow increase of $\underline{m}_N$ can be noted.

Prior investigations were conducted on the assumption that satellite motion occurs in circular orbits. But it appears that from the standpoint of theory improved results can be anticipated if satellite motion in elliptical orbits is examined. In this case a stronger observation signal is obtained because it will be more affected by radial gradients. The above hypothesis is confirmed in the results of numerical calculations. But the practical use of eccentric orbits departing too far from zero involves additional complications:

--the observation material ceases to be homogeneous,

--the process of observation becomes much more complex,

--the system of two satellites becomes unstable more rapidly.

The distance between satellites should be within several hundred kilometers. A change from 200 to 300 kilometers has no practical effect on the accuracy of geoid undulation determination $\underline{N}$.

4. Combining Low-Low Satellite Observation with Ground Gravimetric Measurements

The discussion conducted in the previous section proceeded on the assumption that ground observations are unavailable. Hence the conclusions concerning anticipated accuracy of geoid determination refer to areas not covered by ground observations. In the case where gravimetric observations were made on a studied area, these observations could be combined with satellite observations. This makes it possible to monitor the systematic effects from each of the observation groups. The basic advantage of a combined solution is the distinct stabilization of the frequency range. Improvement in accuracy of geoid determination can be expected.

Only one gravimetric observation made at the determined point with ± 3 mgal error, was added to the previously used model of satellite pair observation, the simplification of calculations having been considered. It was shown that adding a larger number of gravimetric observations increases the accuracy of geoid undulation determination by up to 8%, without affecting the conclusions of this analysis.

Figures 3a, 3b, 3c correspond to figures 1a, 1b, 1c after gravimetric anomalies are added. Figure 3a shows that optimal height is even less differentiated than previously. In both cases, and particularly in the combined solution, we have a wide latitude in determining the orbit in which a satellite pair is to be located.

The range of steady accuracy shrinks for higher degree and order reference fields. It is obvious that the optimal heights on Fig. 3b and on Fig. 1b are further apart from each other as $\underline{L}$ increases.

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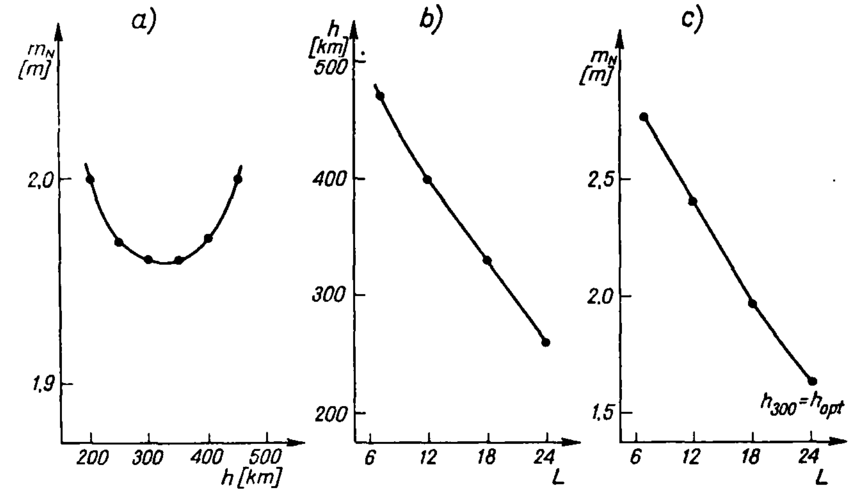

Fig. 3. a. Optimal satellite height for reference field $\underline{L}$ = 18 (share of gravimetric observations); b. Dependence of optimal height on degree and order of reference field (share of gravimetric observations); c. Accuracy of geoid undulation determination from observations at 300 km height and at optimal height as a function of degree and order of reference field (share of gravimetric observations).

Results of a comparison of Fig. 3c and Fig. 1c and an analysis made taking a larger number of observations Δg into account, show that the gain in accuracy which can be anticipated by including gravimetric observations in the calculations, is from 10 to 25%. The addition of gravimetric observations results in higher accuracies and also increases the optimal satellite height.

5. Conclusions

Using observations of low-low satellite relative velocity and applying the collocation method, the local geoid determination can be corrected. The

following conclusions can be drawn from the analysis:

--it is sufficient to have observation material dispersed in a $7^{o} \times 7^{o}$ area at a satellite height $h = 300$ km.

--it is sufficient if the interval between observation profiles is on the order of 3^{o}. Coverage of the entire earth with such a dense collection of satellite pair observations requires four days in the case of a satellite in a polar orbit.

--a 200 to 300 km change in distance between satellites has no significant effect on accuracy of results.

--for every reference field of defined degree and order, there exists an optimal height at which satellite pair observations should be conducted.

--universal height is $h = 300$ km. When harmonic factors are not correlated, accuracy of geoid determination will be $\pm$ 2 meters with a reference field (18, 18).

/26 --to correct local geoid determination, the accuracy of satellite pair relative velocity observations must be higher than $\pm$ 0.5 mm/s, with a geoid global solution accuracy no lower than $\pm$ 5 m.

--combinations of satellite pair observations with ground measurements made on restricted areas greatly improve results, and it particularly increases geoid determination accuracy. In this case, accuracy correction may be as high as 25%. Furthermore, combining the processing of satellite pair observations with gravimetric measurements makes it possible to monitor the systematic effects of each of the observation groups.

The above conclusions depend upon the choice of covariant function. But if the ranges of the initial parameters obtained from contemporary statistical estimates are real, than the differences to which the use of various functions and covariances lead are very small. It should be

emphasized that even when these are large differences between the examined functions of covariance, the results obtained in the analysis process and the observed relations, maintain the same appearance.

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